

Low-Noise Receivers: S-Band Parametric Upconverter Development

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The combination of a cryogenically-cooled parametric upconverter and a higher frequency maser post amplifier has been proposed as a method of achieving maser-like receiver noise temperatures over much larger instantaneous bandwidths and tuning ranges than are presently obtainable with masers in the range of 1 to 18 GHz. An experimental 2.0- to 2.5-GHz parametric upconverter/maser system has been developed to explore these possibilities. Initial tests of this system have resulted in an effective input noise temperature of 3.1 K at 2295 MHz and 3.2 K at 2388 MHz. The parametric upconverter has logged over 1500 hours at 4.5 K and has undergone 5 thermal cycles (300 K to 4.5 K to 300 K) without degradation.

I. Introduction

Recent advances in many areas of technology have made possible the development of an ultralow-noise receiving system that can exhibit noise temperatures similar to those of microwave maser amplifiers, while providing instantaneous bandwidths and tuning ranges many times greater than those of present maser amplifiers in the 1- to 18-GHz range. This system is comprised of a cryogenically-cooled, upper-sideband parametric upconverter (Ref. 1) followed by a maser amplifier operating at a much higher frequency where wide bandwidth and large tuning ranges have been achieved. Two recent developments in particular have made these performance levels possible: the first is the availability of very high-quality gallium arsenide varactor diodes with low package parasitic reactances, and the second is the recent development of a

wideband microwave maser amplifier (Ref. 2), which tunes over the range of 19 to 26 GHz.

To evaluate the feasibility of this type of system for future use in the DSN, an S-band-to-K-band cryogenically cooled parametric upconverter¹ and a K-band maser have been developed, assembled, and tested at JPL. A block diagram of the experimental system is shown in Fig. 1, and a photograph of the completed package is shown in Fig. 2. Following sections of this report will describe each of the system compo-

¹The parametric upconverter described in this report was developed by AIL, a division of Cutler-Hammer, Melville, L.I., N.Y., under contract to JPL.

nents, provide a theoretical noise temperature analysis, and present performance measurements obtained to date.

II. S-Band Parametric Upconverter

The S-band-to-K-band parametric upconverter (Ref. 3), shown in Fig. 3, has a coaxial signal input circuit and a varactor mount, pump circuit, and (sum) output circuit in K-band waveguide. The input circuit consists of a Type N input connector, a bias tee, which provides diode bias voltage via the input coaxial center conductor, and a matching and tuning section. The varactor diode mount contains a pair of matched diodes mounted across a K-band waveguide in a balanced configuration. This configuration isolates the input circuit from pump, output, and image frequency components, therefore eliminating the need for input circuit filtering with the attendant insertion loss. Separation of pump and output frequency components is accomplished by two bandpass filters. Waveguide spacers and reduced-height sections (not labeled in Fig. 3) provide impedance transformation and tuning at the output, pump, and image frequencies.

The upconverter measures 8 dB of net gain with a 3-dB instantaneous bandwidth of approximately 500 MHz when operating at a physical temperature of 4.5 K. Input return loss measures -7 dB or better from 1950 to 2450 MHz, with the region of best input match (return loss ≥ -10 dB) between 2250 and 2420 MHz. Note that these parameters, which vary considerably with bias current level, were measured at a varactor bias current of 1 to 2 μ A. Subsequent noise temperature measurements (described in Section VI of this article) have demonstrated that the best midband noise performance occurs with zero bias current. Therefore, gain, bandwidth, and other RF parameters must be examined after optimum bias settings (for best noise performance) have been determined.

The maser pump rejection filter (Fig. 1) located at the output port of the upconverter is necessary to prevent maser pump power leakage from combining with upconverter pump power in the varactor diodes to produce spurious in-band interfering signals. The present filter is of the "waffle-iron" type and exhibits sufficient attenuation at the maser pump frequency (and its harmonics) to permit noise temperature measurements. An operational upconverter/maser system for the DSN (where received signal levels can be as low as -180 dBm) would require an interstage filter with much higher attenuation at these frequencies.

III. K-Band Reflected Wave Maser (Post Amplifier)

The K-band reflected wave maser is a four-stage, ruby-

filled waveguide traveling wave structure operating at 4.5 K (Figs. 4 and 6). A circulator is used to direct input signals into each ruby-filled waveguide section where maser amplification occurs; on reaching the end of the filled waveguide section, the signal is reflected back to the input and is amplified a second time before passing through the input circulator and onto the next stage. Additional circulators (Fig. 5) are used to increase interstage isolation. The three sections shown in Fig. 4 are combined into the single assembly shown in Fig. 6 with the superconducting magnet required for maser operation at the left.

When the maser is tuned to the upconverter output frequency, the maser pump frequency is modulated to cover a 1-GHz range centered near 51 GHz. Pump power (75 to 100 mW) is supplied with a Siemens Corp. model number RW060 backward wave oscillator. Overall maser gain is 30 to 40 dB with 60 to 250 MHz of instantaneous bandwidth depending on the frequency of operation. The limited instantaneous bandwidth available at present is due to magnetic field nonlinearities in the superconducting magnet. This condition does not affect the validity of upconverter/maser system noise temperature measurements, but it does require that the maser be tuned to the specific frequency of interest within the upconverter bandwidth so that maser gain and effective input noise temperature (4.7 ± 0.5 K) are maintained.

This particular maser is a copy of the K-band reflected-wave maser developed by JPL and NRAO²; a complete technical description of which is soon to be published (Ref. 2). Continuing K-band maser development work by NRAO has produced a 500-MHz bandwidth. This improvement was accomplished by using a larger superconducting magnet with the same maser structure as described here (Ref. 4). Initial development work on the reflected-wave maser concept began in 1972 under a California Institute of Technology President's grant to the University of California at San Diego and the Jet Propulsion Laboratory (Ref. 5).

IV. Closed-Cycle Refrigerator

A standard 1-W JPL 4.5-K closed-cycle refrigerator (CCR) (Refs. 6, 7) is used to house the upconverter/maser assembly. Figure 2 shows the packaged system with attached pump sources. Figure 7 shows the CCR with vacuum housing, input transmission line, and radiation shields removed.

²The development of this maser design was the result of a joint research effort between the National Radio Astronomy Observatory, operated by Associated Universities, Inc., under contract with the National Science Foundation, and the JPL/CIT under contract NAS7-100 sponsored by NASA.

The S-band input transmission line (Fig. 8) utilizes an existing waveguide-to-coax design (Ref. 8) that cools the entire length of coaxial center conductor to 4.5 K. The noise temperature contribution from this transmission line is calculated to be 0.5 K. A length of 3.5-mm (0.141-inch) O.D. semirigid cable, all at a 4.5-K physical temperature, couples the input signal from the CCR input transmission line to the upconverter input connector. Two liquid-helium heat exchangers are required to properly maintain the upconverter diode mount, superconducting magnet, maser circulator assembly, maser structure, and related interconnecting waveguide components at 4.5 K.

Pump inputs in WR 42 and WR 19 waveguide (Figs. 2, 7) are used for excitation of the parametric upconverter (21.76 GHz) and the maser ruby structure (51 GHz), respectively. A WR 42 waveguide is used for the maser output at 24 GHz. Other inputs to the 4.5 K station include the magnet charging system and normal instrumentation wires.

New, larger heat shields were required because of the increased size of the 4.5 K assembly. The increased thermal radiation load from this source, combined with the total input pump power (120 to 150 mW) and the heat conduction associated with the many input connections to the 4.5 K station, have severely loaded the 1-W capacity of the CCR. Operation in a 35°C ambient environment and rapidly repeated retuning of the superconducting magnet have resulted in several CCR warmups. The system, while functional for testing, is very marginal. The development of CCRs with greater 4.5 K cooling capacity is planned.

The large mass (≈ 9 kg) attached to the 4.5-K station required changes in the support structure and precool system. Mechanically, the upconverter/maser assembly and 4.5-K station are supported by the input waveguides and a solid copper block connected to the 15-K station via the hydrogen thermal switch (Fig. 7). A larger nitrogen precool heat exchanger and copper sheath were attached directly to the superconducting magnet assembly since heat transfer through the Hyperco 27 magnet material is low. Additional copper straps are used to aid heat transfer. These changes have reduced the precool time (ambient to 80 K) from three hours to one hour; a total of eight hours is required to cool down to 4.5 K. The 15-K station appears to have additional cooling capacity to decrease the cooldown time; a larger capacity hydrogen thermal switch should be developed to improve heat transfer from the 4.5-K station to the 15-K station during the cooldown process. A new digital thermometer³ is being

used to monitor CCR temperatures replacing the traditional thermocouple sensors. The direct readout feature from 2 to 300 K enables more convenient and more accurate measurements than has previously been achieved with thermocouple instrumentation.

V. Theoretical Noise Temperature Estimate

Table 1 itemizes the calculated *contribution* to the effective input noise temperature (at the room temperature waveguide input flange) of each component in the upconverter/maser system as diagrammed on the left side of the table. These calculations do not include the effect of input or output circuit mismatch. Therefore, the results are applicable only to midband frequencies where upconverter gain is maximum and input and output reflection losses are small. At 2295 MHz, upconverter gain is within 1 dB of maximum and input return loss between -10 and -13 dB (depending on bias setting), and it is valid to compare noise temperature measurements obtained at this frequency with the theoretical values in Table 1.

As indicated in the table notes, the parameter values used in the calculation are best estimates based on handbook values, previously measured data on similar parts, or data from the various references. Upconverter input and output losses L_3 and L_4 are estimated from (1) measurements reported in Ref. 3, and (2) the difference between theoretical gain (assuming no circuit losses but including calculated diode losses) and actual measured gain.

The physical temperature of the diode junctions has a substantial effect on the overall system effective noise temperature according to Table 1: 2.5 K if the diode junctions experience no pump heating, and 3.5 K if the diode junctions are heated to 20 K. The uncertainties in the estimates of the various contributions listed in Table 1 have not been rigorously analyzed. However, it is believed that the sum of the worst case errors for all other contributions does not exceed the ± 0.5 K resulting from the two different diode junction temperature assumptions discussed above. Workers in the field have estimated this pump heating effect to be anywhere between 0.5 K and 30 K above the ambient temperature. Careful system noise temperature measurements as a function of bias level and upconverter pump power level may shed some light on this important question of pump diode heating.

Upconverter diode gain G_D (see Table 1, note f) is approximately proportional to the ratio of output frequency to input frequency. For the S-band to K-band upconverter, this ratio is high, and therefore noise contributions from upconverter

³Model DRC-70C, Digital Thermometer/Controller manufactured by Lakeshore Cryotronics, Inc., Columbus, Ohio.

output circuit losses, interstage losses, and maser input noise temperature are small. For this reason, the system input noise temperature is, in fact, lower than the 4.7-K maser input noise temperature. Consider similar varactor diodes used in a 8.5-GHz to 24-GHz upconverter. G_D for this case would be approximately 3 dB and system input noise contributions from L_4 , L_5 , and T_M would be substantially larger. If maximum performance is to be obtained from upconverter/maser systems at X-band or K_u-band, careful effort will be needed to minimize the loss of each component in the system, and the benefits of using a higher frequency maser postamplifier should be explored.

VI. Noise Temperature Measurements

Noise temperature measurements of the upconverter-maser system were performed at JPL. A feed horn was attached to the input waveguide flange and a large piece of microwave absorber was used as an ambient temperature termination for the horn (see Fig. 9). System noise temperature data are obtained by covering the feed horn with the absorber and then removing the absorber, allowing the horn to view the cold sky. Total operating system noise temperature is obtained by making precision power-level measurements with and without the absorber in place. A detailed description and analysis of noise temperature calibrations using ambient terminations has been published by C. T. Stelzried. (Ref. 10)

Initial measurements to date have resulted in a total system operating noise temperature of 9.4 K at 2295 MHz and 9.5 K at 2388 MHz. Best estimates of noise contributions for the parts of the system are given in Table 2. The noise contribution estimates for the sky and horn are those used in previous S-band maser noise calibrations (Ref. 8). The follow-up receiver contribution is measured by making a system power measurement with the maser pump source on and off. When these three contributions are subtracted from the total system noise temperature, the effective input noise temperature for the upconverter/maser system is found to be 3.1 K at

2295 MHz and 3.2 K at 2388 MHz. These values fall within the theoretical estimate of 2.5 to 3.5 K obtained in Table 1.

The upconverter noise temperature can be estimated by subtracting component noise contribution estimates (Table 1) from the system effective input noise temperatures reported above. This calculation results in an input noise temperature for the upconverter of less than 2 K.

VII. Reliability

The ability of the parametric upconverter to withstand repeated temperature cycling from room temperature to 4.5 K and to operate reliably at this temperature for extended periods of time is of importance. If a cryogenic component is to become an operational reality in the DSN, it must demonstrate high performance in the above areas as well as in areas of RF performance. To date, the upconverter itself has logged over 1500 hours at 4.5 K and has undergone 5 full temperature cycles of 300 K – 4.5 K – 300 K without degradation.

VIII. Conclusions

The combination of an experimental cryogenically-cooled S-band upconverter and a K-band maser postamplifier has demonstrated an effective input noise temperature of 3.1 K at 2295 MHz and 3.2 K at 2388 MHz. These initial results compare favorably with input noise temperatures of 2.0 to 2.1 K achieved with the best S-band maser amplifiers (Ref. 8). These figures represent a remarkable achievement in noise performance for a system which has a potential instantaneous bandwidth of 400 to 500 MHz at S-band frequencies.

Testing of this system will be continued. Feed horn configurations that are suitable for other frequencies within the 2.0 to 2.5-GHz range will be obtained so that system noise temperature can be evaluated across the entire upconverter bandwidth. Other RF parameters will be investigated and reliability in the cryogenic environment will be monitored.

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Table 1. Theoretical noise temperature estimate, $f_s = 2.3$ GHz

System schematic diagram	Component description	Component loss L , or gain G , or input noise temperature T	Value of L , G , or T	Component contribution to effective input noise temperature at S-band waveguide input port	
				Contribution ^{a,b}	Value
	S-band input transmission line	L_1	0.05 dB ^c	— ^c	0.5 K ^c
	0.141 semirigid cable	L_2	0.03 dB ^d	$L_1 (L_2 - 1) T_{CCR}$	0.03 K
	Upconverter input circuit loss	L_3	0.4 dB ^e	$L_1 L_2 (L_3 - 1) T_{CCR}$	0.44 K
	Varactor diodes	G_D T_D	$G_D = 9$ dB ^f $T_D = 0.3$ K ^{g,h} $T_D = 1.2$ K ^{h,i}	$L_1 L_2 L_3 T_D$	0.3 K ^g 1.3 K ⁱ
	Upconverter output circuit loss	L_4	0.6 dB ^e	$\frac{L_1 L_2 L_3 (L_4 - 1)}{G_D} T_{CCR}$	0.09 K
	Interstage loss, including pump rejection filter	L_5	0.9 dB ^d	$\frac{L_1 L_2 L_3 L_4 (L_5 - 1)}{G_D} T_{CCR}$	0.17 K
	Maser	T_M	4.7 K ^j	$\frac{L_1 L_2 L_3 L_4 L_5}{G_D} T_M$	0.93 K
Total system effective input noise temperature					2.5 K ^g 3.5 K ⁱ

Table 1. Theoretical noise temperature estimate, $f_s = 2.3$ GHz (contd)

^aCCR physical temperature $T_{CCR} = 4.5$ K.

^bIn the equations, losses L and gains G are dimensionless ratios.

^cTemperature along this line varies from 300 K to 4.5 K. Q measurements, insertion loss, and temperature gradient calculations were used to determine 0.5 K contribution.

^dEstimated from published values, previous measurements of similar components, and measured variations of insertion loss vs temperature.

^eSee Section V.

^fFor minimum noise tuning:

$$G_D \approx \frac{f_o}{f_s} \frac{1}{1 + \frac{f_o}{M}} \quad (\text{Ref. 10})$$

where

G_D = conversion gain of varactor diodes

M = varactor diode figure of merit $m_1 f_c$

= 80 GHz (Ref. 3)

f_o = output frequency

= 24 GHz

f_s = input frequency

= 2.3 GHz

Substituting:

$$G_D = 8.0 = 9 \text{ dB}$$

^gIf diode junction temperature is 4.5 K, i.e., no pump heating.

^hFor minimum noise tuning:

$$T_D \cong \frac{2 f_s}{M} T_J \quad (\text{Ref. 10})$$

$$\approx 0.3 \text{ K for } T_J = 4.5 \text{ K}$$

$$\approx 1.3 \text{ K for } T_J = 20 \text{ K}$$

where

T_D = effective input noise temperature of varactor diodes due to series resistance.

T_J = physical temperature of diode junction.

ⁱIf diode junction temperature is 20 K.

^jCalculation of maser effective input noise temperature gives $T_M = 4.7 \text{ K} \pm 0.5 \text{ K}$ (Ref. 2)

Table 2. Noise contributions for the upconverter/maser system

Part of system	Noise contribution, K	
	2295 MHz	2388 MHz
Sky (includes atmosphere and cosmic background)	4.9	4.9
Horn (includes mode generator and transition)	1.2	1.2
Upconverter/Maser System	3.1	3.2
Follow-up receiver	0.2	0.2
Total operating system noise temperature T_{op}	9.4	9.5

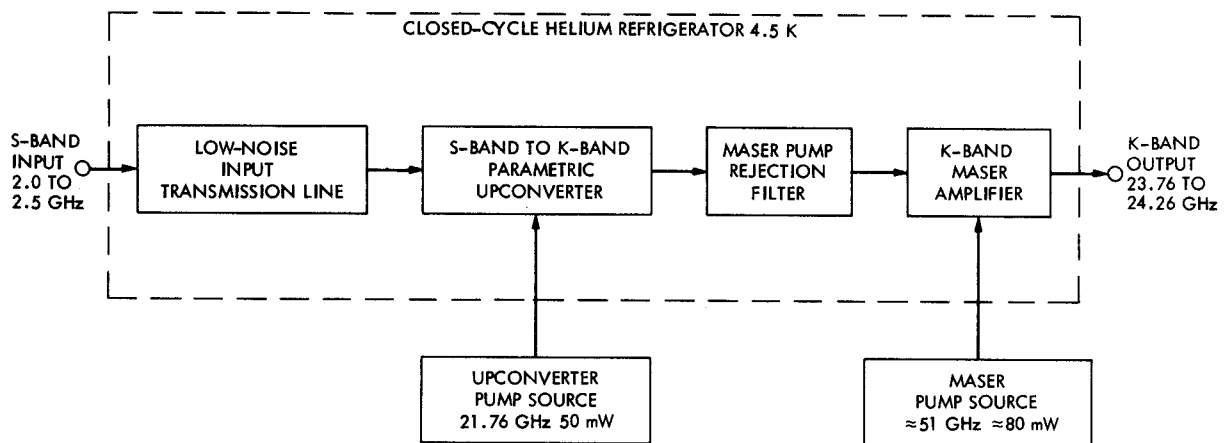


Fig. 1. Block diagram of upconverter/maser/CCR system

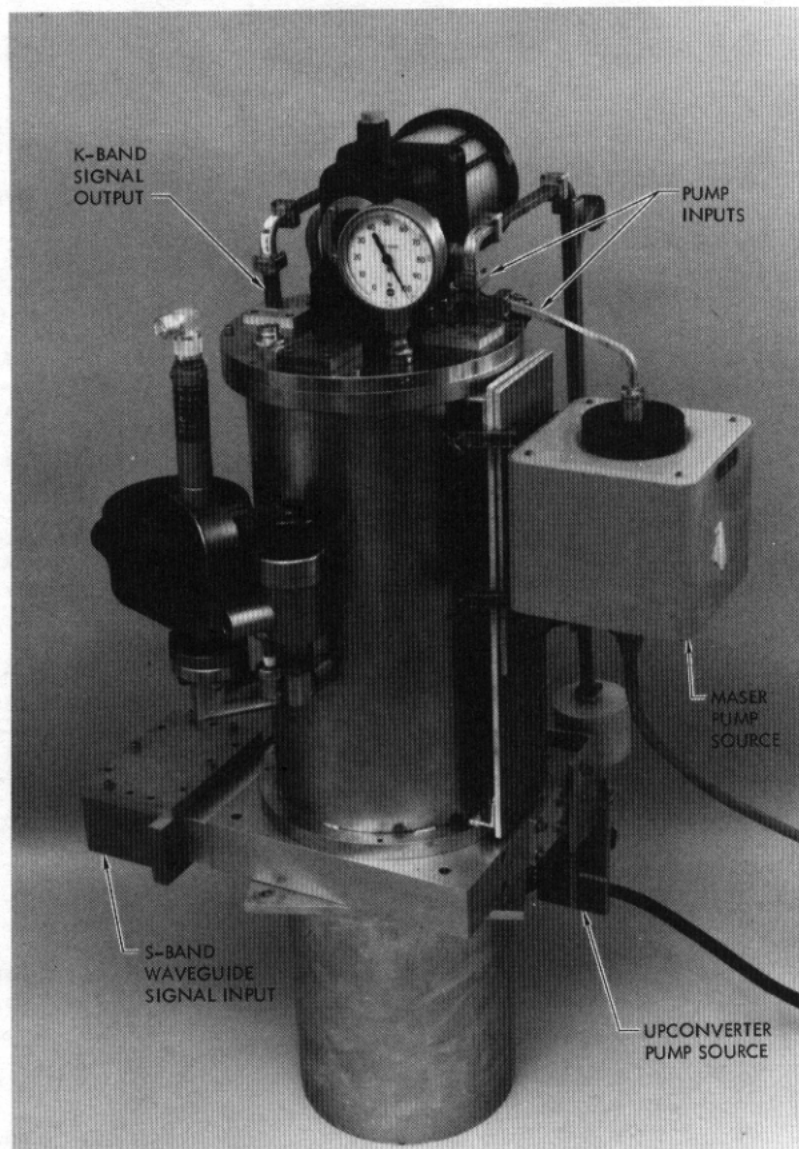


Fig. 2. Packaged upconverter/maser/CCR system

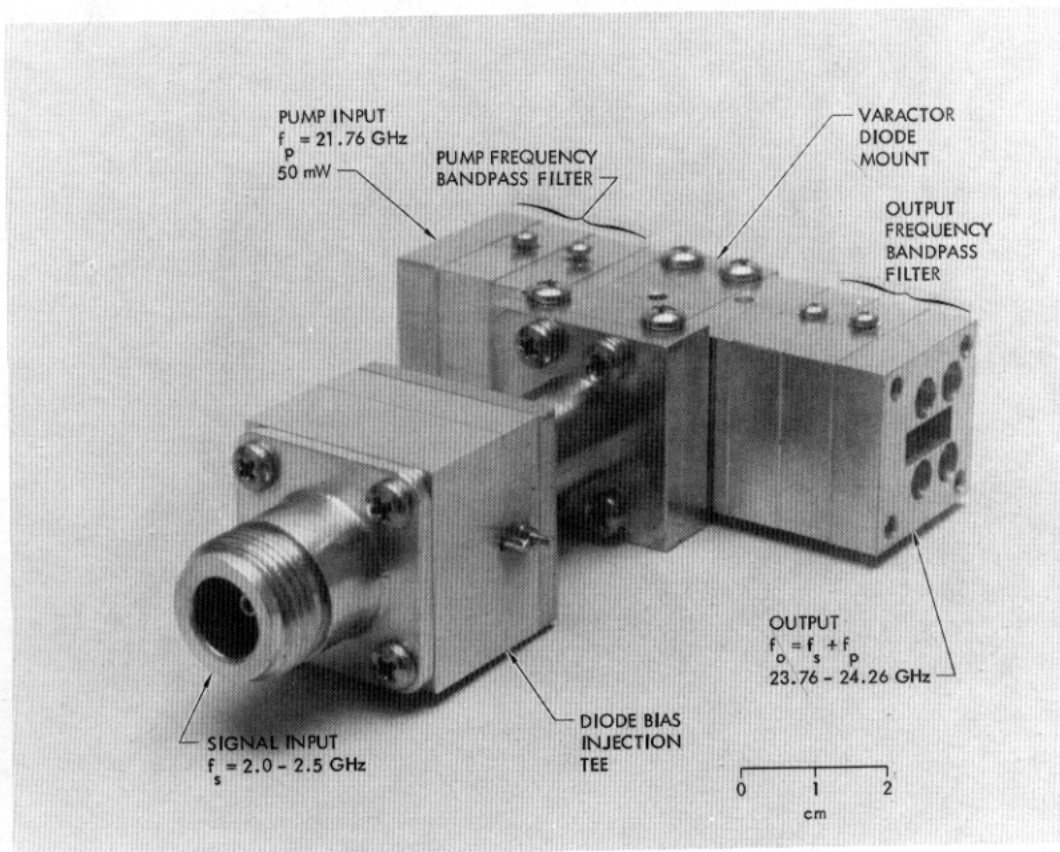


Fig. 3. S-band parametric upconverter

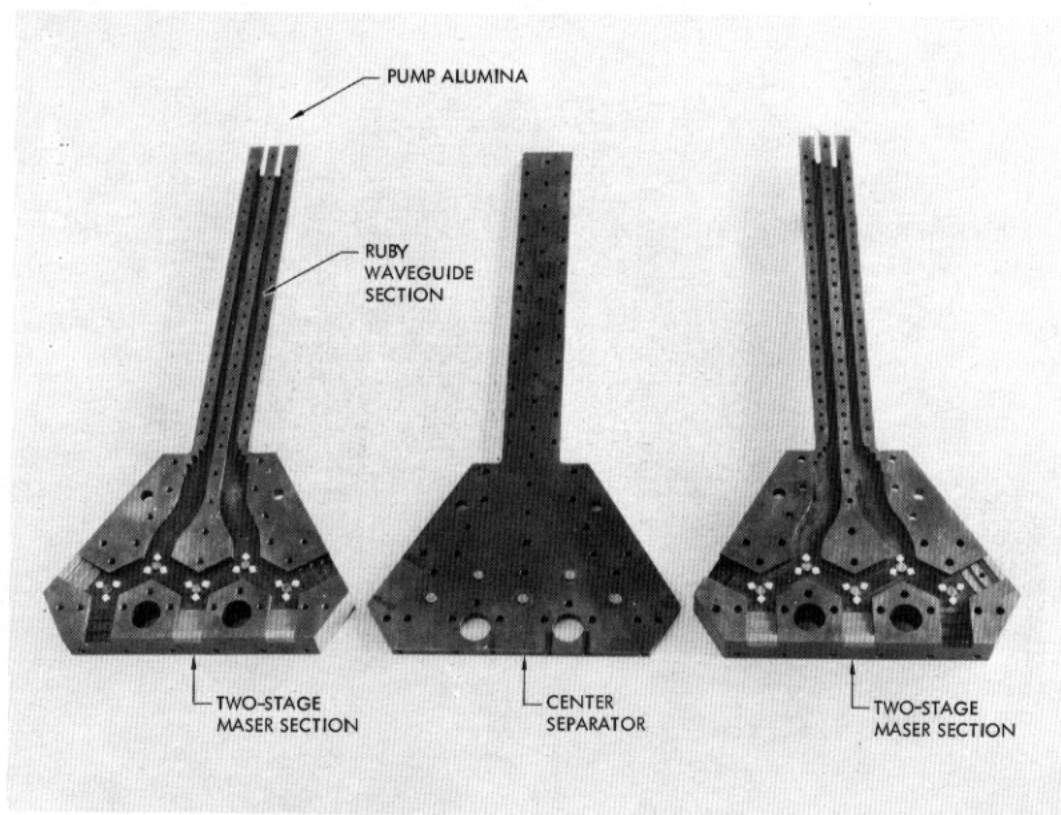


Fig. 4. K-band maser structure

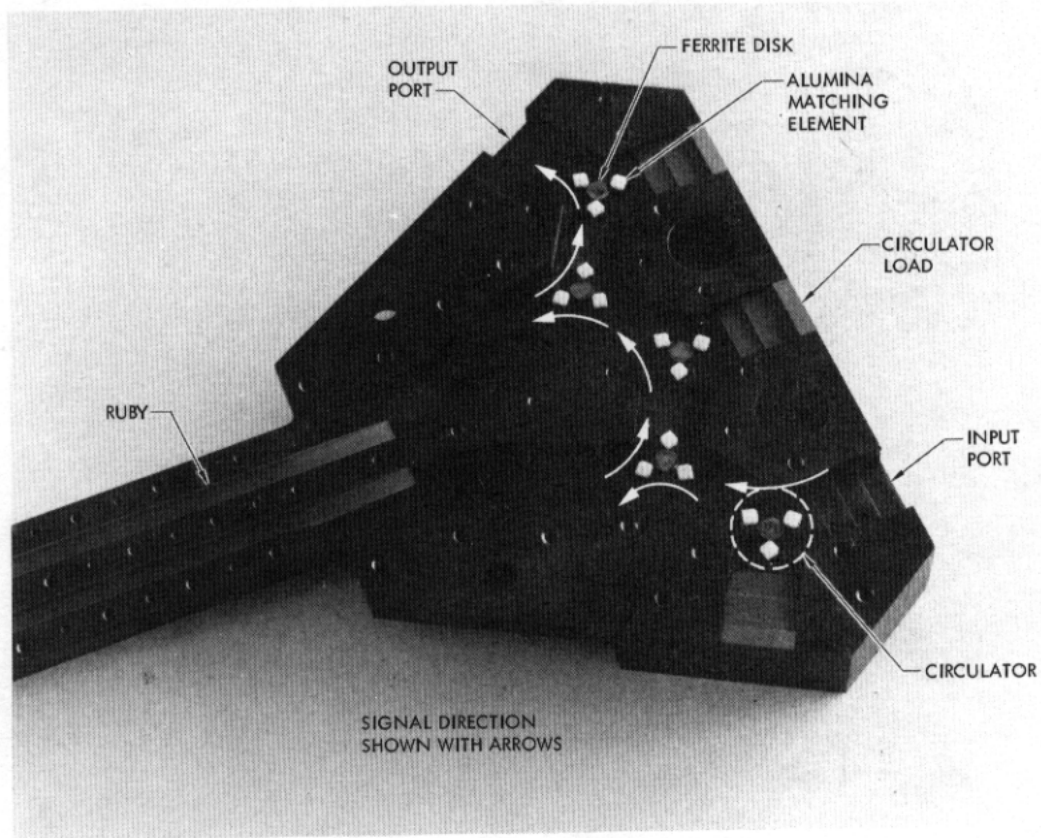


Fig. 5. K-band maser circulator and ruby waveguide detail

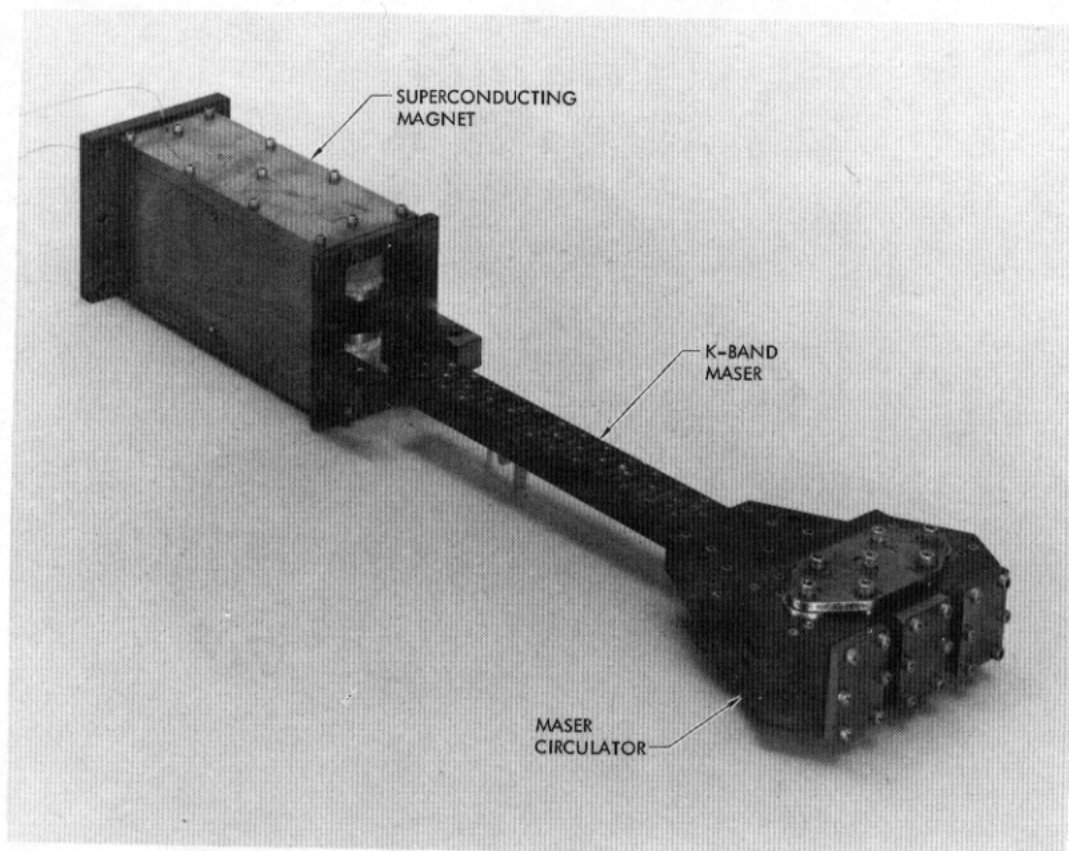


Fig. 6. K-band maser with superconducting magnet

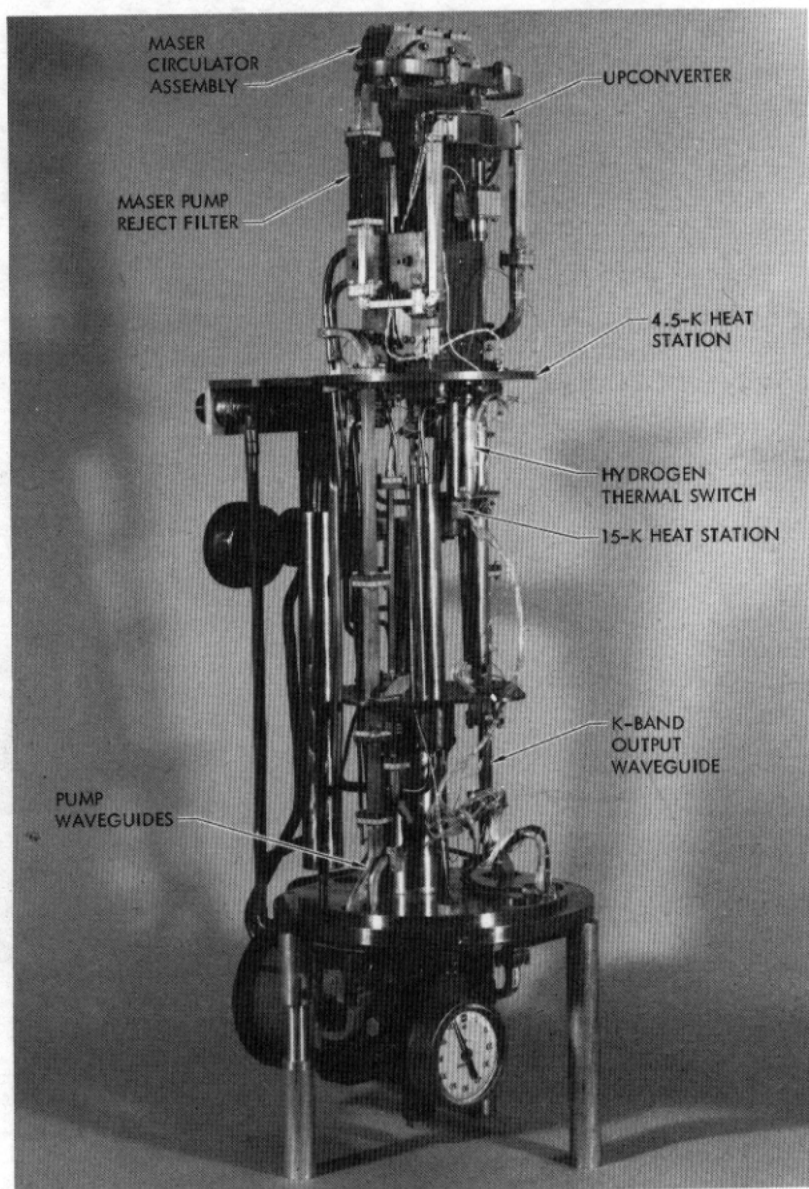


Fig. 7. CCR assembly

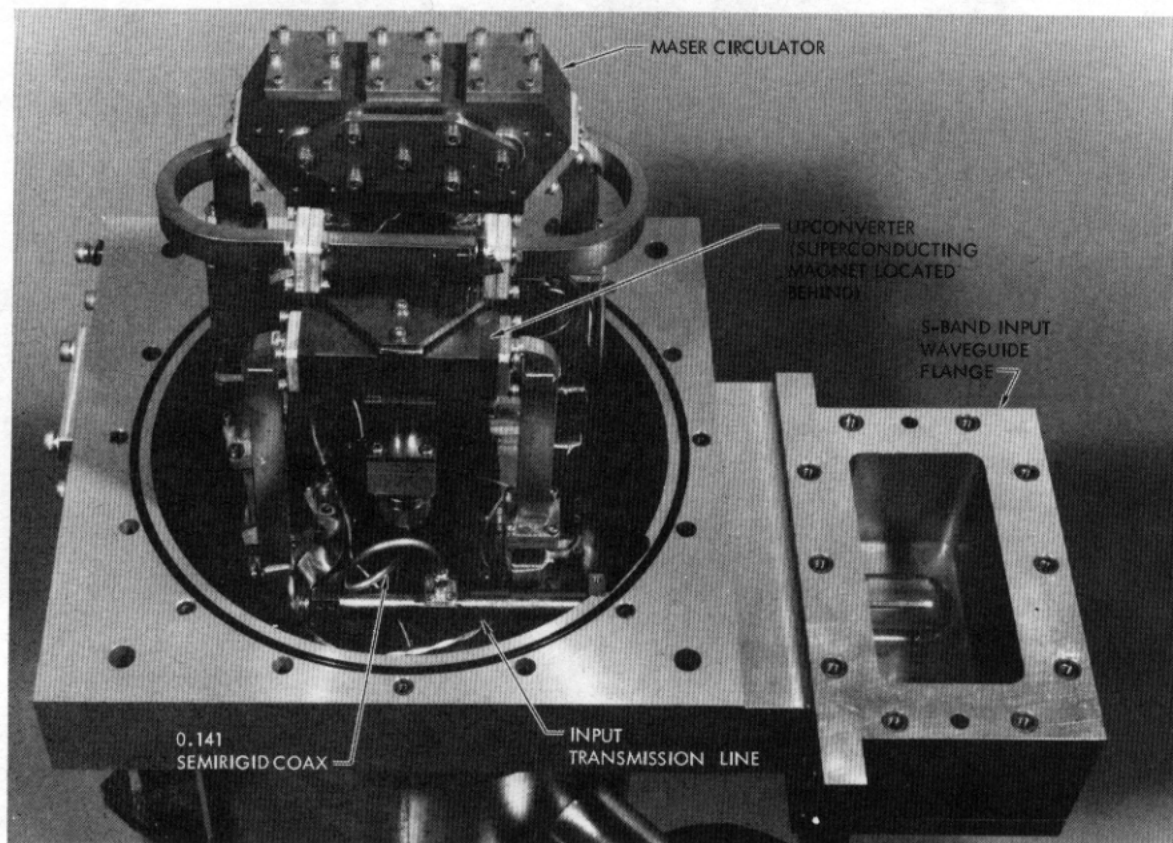


Fig. 8. CCR partially disassembled, showing input transmission line and 4.5-K components

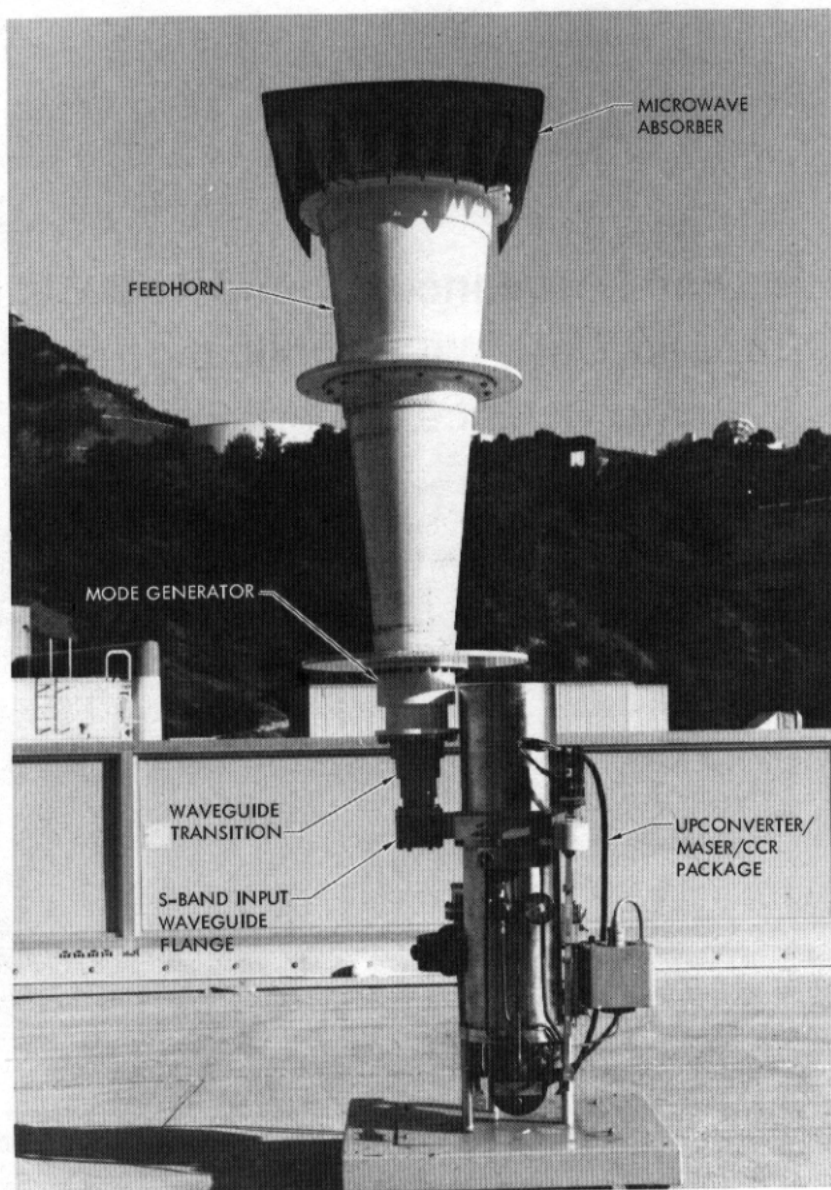


Fig. 9. System for measurement of upconverter/maser noise temperature